AEDC-TSR-81-V18

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WIND TUNNEL TESTING OF A WINDSHIELD MATERIAL FOR SUPERSONIC AIRCRAFT

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Calspan Field Services, Inc.

May 1981

Final Report for Period April 9-10, 1981

ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE STATION, TENNESSEE
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

APPROVAL STATEMENT

This report has been reviewed and approved.

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FOR THE COMMANDER

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Aerospace Flight Dynamics Testing
Deputy for Operations

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AEDC-TSR-81-V18	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Wind Tunnel Testing of a Windshield Material for Supersonic Aircraft		5. TYPE OF REPORT & PERIOD COVERED Final Report April 9-10, 1981
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. W. Stallings and A. S. Hartman, Calspan Field Services, Inc., AEDC Division		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center Air Force Systems Command Arnold Air Force Station, Tennessee 37389		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 62201F Control No. 2402
11. CONTROLLING OFFICE NAME AND ADDRESS AFWAL/FIER Wright-Patterson Air Force Base, OH 45433		12. REPORT DATE May 1981
		13. NUMBER OF PAGES 42
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in Defense Technical Information Center (DTIC).

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

wind tunnel testing
materials testing
aerodynamic heating
heat transfer
windshields

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Wind tunnel tests of windshield material intended for use on supersonic aircraft were conducted in the von Kármán Facility Hypersonic Wind Tunnel B at a free-stream Mach number of 6 and tunnel stilling chamber conditions of 146 psia and 495°F. The wedge technique was used to provide a local Mach number of 2.5 over the windshield specimen. Selected results are presented to illustrate the test techniques and typical data obtained.

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APPENDIXES

NOMENCLATURE*

ALPI	Indicated pitch angle, deg
AWT	Theoretical adiabatic wall temperature, °R (see Appendix III)
AWX	Experimental adiabatic wall temperature, °R (see Appendix III)
C1	Gardon gage calibration factor measured at 530°R, Btu/ft^2-sec/mv
C2	Temperature-corrected Gardon gage calibration factor, Btu/ft^2-sec/mv. (see Eq. 1)
CHI	Pressure ratio (see Appendix III)
E	Gardon gage output, mv
GAGE NO.	Gage identification number
HT	Theoretical heat-transfer coefficient Btu/hr-ft^2-°R (see Appendix III)
H(TT)	Experimental heat-transfer coefficient based on TT, QDOT/TT-TW), Btu/ft^2-sec-°R
HX	Experimental heat-transfer coefficient including radiation effects, Btu/hr-ft^2-°R (see Appendix III)
iCi	Gardon gage identification number (see Fig. 5)
iPi	Pressure port identification number (see Fig. 5)
iSi	Windshield thermocouple identification number, (see Fig. 6)
KG	Gardon gage temperature calibration factor, °R/mv
L	Turbulent boundary layer running length, ft
M	Free-stream Mach number
MDOT	Test fixture cavity cooling air flow rate, lbm/min
MLT	Calculated wedge surface Mach number (see Appendix III)
MLX	Experimental local Mach number (see Appendix III)
P	Free-stream static pressure, psia
PFi	Test fixture pressures, psia

*The AEDC/VKF standard nomenclature has been modified to include parameters requested by Rockwell International.

PHI	Theoretical reference temperature function (see Appendix III)
PLT	Calculated local static pressure on wedge surface, psia
PORT NO.	Pressure orifice identification number
PT	Tunnel stilling chamber pressure, psia
PW	Measured wedge surface pressure, psia
QDOT	Heat-transfer rate, Btu/hr-ft^2
QSW	Radiant heat flux, Btu/hr-ft^2 (see Appendix III)
RE	Free-stream unit Reynolds number, ft^{-1}
REC	Theoretical recovery factor (see Appendix III)
RUN	Data set identification number
T	Free-stream static temperature, °R
TGDEL	Temperature differential from the center to the edge of Gardon gage disc, °F
TGE	Gardon gage edge temperature, °R
THETAT	Wedge oblique shock wave angle, deg
Ti	Measured test fixture cavity cooling air temperature, °F
TLT	Calculated wedge surface temperature, °R
TLX	Experimental local static temperature, °R (see Appendix III)
TOPi	Sequence camera identification (see Table 5)
TST	Test section wall temperature, °R
TT	Tunnel stilling chamber temperature, °R
TW	Model surface temperature, °R
T*T	Theoretical reference temperature, °R (see Appendix III)
VELT	Calculated local velocity on wedge surface, ft/sec
WA	Wedge angle, deg
X,Y	Orthogonal body axis system directions (see Fig. 3)

1.0 INTRODUCTION

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 62201F, Control Number 2402, at the request of the Air Force Wright Aeronautical Laboratory (AFWAL) for the Rockwell International, North American Aircraft Division. The AFWAL project manager was Mr. C. A. Babish and the RI project engineer was Mr. V. E. Wilson. The results were obtained by Calspan Field Services, Inc./AEDC Division, operating contractor for the Aerospace Flight Dynamics testing effort at the AEDC, AFSC, Arnold Air Force Station, Tennessee. The tests were conducted in the von Kármán Gas Dynamics Facility (VKF), Hypersonic Wind Tunnel (B) under AEDC Project No. C072VB.

The primary objective of this test program was to obtain data to validate aerothermodynamic analysis methods which were being used to predict windshield performance. This was accomplished by exposing a specific laminated windshield design to conditions in the wind tunnel which simulated portions of a high-performance aircraft flight envelope. Thus, a second objective was included; i.e., the evaluation of the response of the particular windshield design to the simulated flight conditions.

To meet the program objectives, tests were conducted in the 50-in. diameter Hypersonic Wind Tunnel (B) on April 9 and 10, 1981. The tunnel was operated at a Mach number 6 with a stilling chamber pressure of 146 psia and stilling chamber temperature of 495 and 550°F.

To provide the desired flow conditions over the windshield specimen, the wedge technique developed in the VKF for materials testing was used. With this technique, the specimens to be tested are attached to a large wedge for injection into the tunnel flow. The oblique shock wave generated by the wedge reduces the hypersonic free-stream Mach number to a supersonic level. The flow field conditions over the wedge can be controlled by changing the wedge pitch angle and, if desired, by adjusting the tunnel stilling chamber conditions. A more detailed description of this technique may be found in Ref. 1. For this test a special fixture was fabricated on which the windshield specimen formed the upper wedge surface. In a sealed cavity beneath the windshield, aircraft cabin atmosphere could be simulated. The wedge pitch angle was varied during the runs to simulate the changing Mach number and heat load experienced by the windshield during a typical flight.

Several different data acquisition techniques were used to obtain all the desired information from the test. To define the convective heating environment on the windshield, a calibration phase was conducted. For these runs the windshield was replaced by a steel plate instrumented with Gardon gages and pressure taps. For the actual windshield tests, two identical specimens were used. One of these contained several thermocouples mounted at various locations within the laminations. The other was a clear panel, providing an unobstructed view of a grid line pattern in the cavity beneath. Sequence cameras photographed the grid pattern during a tunnel run to record any distortion of the windshield.

All test data have been transmitted to Rockwell International and AFWAL as described in Table 1. Inquiries to obtain copies of the test data should be directed to AFWAL/FIER, Wright-Patterson AFB, OH 45433. A microfilm record of the tabulated data has been retained in the VKF at AEDC.

2.0 APPARATUS

2.1 TEST FACILITY

Tunnel B (Fig. 1) is a closed circuit hypersonic wind tunnel with a 50-in. diam test section. Two axisymmetric contoured nozzles are available to provide Mach numbers of 6 and 8 and the tunnel may be operated continuously over a range of pressure levels from 20 to 300 psia at Mach number 6, and 50 to 900 psia at Mach number 8, with air supplied by the VKF main compressor plant. Stagnation temperatures sufficient to avoid air liquefaction in the test section (up to 1350°R) are obtained through the use of a natural gas fired combustion heater. The entire tunnel (throat, nozzle, test section, and diffuser) is cooled by integral, external water jackets. The tunnel is equipped with a model injection system, which allows removal of the model from the test section while the tunnel remains in operation. A description of the tunnel may be found in Ref. 2.

2.2 TEST ARTICLE

The test fixture, with a windshield specimen attached, is shown in Fig. 2a, a photograph which was taken in the tank beneath the Tunnel B test section. Details of the fixture and the laminated windshield specimen are presented in Fig. 3. Three rows of trip spheres were placed on the fixture to insure a turbulent boundary layer over the specimen. For the calibration runs the windshield panel was replaced by a steel plate. The test fixture assembly was supported by a sting which was attached to standard Tunnel B mounting hardware. Installation of the fixture in Tunnel B is shown in Fig. 4.

2.3 TEST INSTRUMENTATION

The instrumentation, recording devices, and calibration methods used to measure the primary tunnel and test data parameters are listed in Table 2a along with the estimated measurement uncertainties. Further descriptions of some of the systems are given below.

Heat transfer rate measurements on the calibration plate were obtained with thermopile Gardon gages which were supplied and calibrated by the VKF. The thermopile gage utilizes vapor-deposited layers of antimony and bismuth to form a thermopile on the back surface of the sensing foil. The gages were 0.025 in. in diam with sensing foil thicknesses of 0.020 in. They were instrumented with iron-constantan thermocouples which provided the gage edge temperature measurement. Gage edge temperatures together with the thermopile output were used to determine the gage surface temperatures and corresponding gage heat transfer rate. These data were then used to compute the local heat transfer coefficient. A total of 13 thermopile gages were installed in the model. A sketch showing the general arrangement of the calibration plate instrumentation is presented in Fig. 5 and dimensional locations of the gages are listed in Table 3.

The Tunnel B standard pressure system was used to measure the calibration plate and test fixture pressures. This system is composed of 16 channels, each with a 1- and a 15-psid transducer. Each channel is connected to an eight-position switching valve, for a total system capability of 128 pressure measurements. A look-ahead pressure level sensing system automatically selects the proper transducer at the time the scanning valves are advanced. Pressure tap locations on the calibration plate are indicated on Fig. 5 and in Table 4. Approximate locations of the test fixture pressures were indicated on Fig. 3.

The imbedded thermocouples used to record temperature histories at various points within the laminated windshield were installed by Rockwell International during specimen fabrication. Exact locations were not available for this report. A sketch showing approximate locations is given in Fig. 6.

A variety of cameras was used to photograph the model during a tunnel run. Two 70mm cameras were mounted on top of the tunnel. One of these looked down at the windshield surface. The other was positioned to view through the windshield to a grid-line target inside the test fixture. A black-and-white television camera on top of the tunnel provided an overall view of the test section. Shadowgraph and schlieren photographs were also taken through tunnel side windows. All photographic data are identified in Table 5.

A total time of exposure to the tunnel flow is also required for data reduction. All the events which occur during a run are timed using the digital clock in the VKF DEC-10 computer, which processes all data from the continuous flow tunnels.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS

A summary of the nominal test conditions is given below.

MACH	PT, psia	TT, °R	WA, deg	MLT	H(TT)*, Btu/ft^2-hr-°R
6	146	955	8	4.9	10.5
			36	1.2	37.3

*at one foot from the leading edge

A test summary showing all configurations tested and the variables for each is presented in Table 6.

3.2 TEST PROCEDURES

In the VKF continuous flow wind tunnels (A, B, C), the model is mounted on a sting support mechanism in an installation tank directly underneath the tunnel test section. The tank is separated from the tunnel by a pair of fairing doors and a safety door. When closed, the fairing doors, except for a slot for the pitch sector, cover the opening to the tank and the safety door seals the tunnel from the tank area. After the model is prepared for a data run, the personnel access door to the installation tank is closed, the tank is vented to the tunnel flow, the safety and fairing doors are opened, the model is injected into the airstream, and the fairing doors are closed. After the data are obtained, the model is retracted into the tank and the sequence is reversed with the tank being vented to atmosphere to allow access to the model in preparation for the next run. The sequence is repeated for each configuration change.

A given injection cycle is termed a run, and all the data obtained are identified in the data tabulations by a run number.

Model attitude positioning and data recording were accomplished in one of two ways for each model injection. For the calibration runs the model attitude was set while in the installation tank and the model was injected at that attitude with data recording taking place automatically at preselected time intervals. For the windshield runs the model was pitched using the sweep mode of operation under the control of the VKF Model Attitude Control System (MACS). With the MACS, model pitch requirements were entered into the controlling computer prior to the test and model positioning was performed automatically by the system. Two different pitch-time trajectories were used, as shown in Fig. 7.

One of the test requirements was that the inside of the test fixture be pressurized to simulate an aircraft cabin atmosphere. This cooling air flow was initiated prior to injection into the tunnel. Locations of the inlet and vent can be seen in Fig. 3. The pressure inside the fixture was monitored while the supply pressure was increased. When the specified cavity pressure was reached, the system was stabilized and the flow then remained constant throughout the tunnel run.

Instrumentation outputs were recorded using the VKF digital data scanner in conjunction with the VKF analog subsystem. Data acquisition was under the control of a Digital Equipment Corporation (DEC) PDP 11/40 computer, utilizing the random access data system (RADS). The procedures used by RADS varied somewhat for the different phases of the test. For the calibration plate runs, all the transducer outputs were scanned automatically at the instant the injection sequence began (lift-off) and again when the model reached centerline. Subsequent scans were initiated manually. The primary heat-transfer data were obtained from a scan about two seconds after centerline. The output of the pressure transducers was monitored, and after the readings were stabilized, the pressure data were recorded. Additional data scans were taken at five to ten second intervals over a total run time of 30 to 60 seconds to obtain additional heat-transfer data.

For the instrumented windshield runs data acquisition was automatic, beginning at lift-off and continuing through a total run time of about twenty minutes. The initial rate was one scan per second. After about four minutes the rate was changed to one scan every fifteen seconds for the remainder of the run.

Primary data for the noninstrumented windshield runs were photographs of the windshield and the grid-line target inside the test fixture. Tunnel and wedge parameters were recorded by taking a data scan at lift-off, centerline, and each time the cameras were triggered, for a total of eleven loops of data during the twenty minute run.

3.3 DATA REDUCTION

Measured stilling chamber pressure and temperature and the calibrated test section Mach number were used to compute the free-stream properties. A perfect gas, isentropic expansion from stilling chamber to test section was assumed.

Data measurements obtained from the thermopile Gardon gages are gage output (E) and gage edge temperature (TGE). The gages are direct reading heat flux transducers and the gage output is converted to heating rate by means of a laboratory calibrated scale factor (C1). The scale factor has been found to be a function of gage temperature and therefore must be corrected for gage temperature changes,

$$C2 = C1\ f(TGE) \tag{1}$$

Heat flux to the gage is then calculated for each data point by the following equation:

$$QDOT = (C2)(E) \tag{2}$$

The gage wall temperature used in computing the gage heat transfer coefficient is obtained from two measurements; the output of the gage edge thermocouple (TGE) and the temperature difference (TGDEL) from the gage center to its edge. TGDEL is proportional to the gage output, E, and is calculated by:

$$TGDEL = (KG)(E) \tag{3}$$

The gage wall temperature is then computed as

$$TW = TGE + 0.75\ TGDEL \tag{4}$$

where the factor 0.75 represents the average, or integrated value across the gage.

The VKF standard Gardon gage data reduction procedure was used to compute model local heat transfer coefficients. The procedure averages five consecutive samples of gage output, (E) commencing with the data loop recorded at least one second after the model arrives at tunnel centerline. The average output is then compared to each individual reading used in the average to check for "wild" points. If the individual readings differ from the calculated average by more than ±2 percent or ±15 counts, whichever is larger, an asterisk (*) is printed next to the tabulated value of QDOT. The gage edge temperature (TGE) was averaged in the same manner with ±5 deg allowable deviation from the average.

The heat-transfer coefficient for each gage was computed using the following equation

$$H(TT) = \frac{QDOT}{(TT - TW)} \qquad (5)$$

where QDOT and TW were obtained from gage measurements. Calculation of the heat-transfer coefficient in this form allowed quick comparison with similar data obtained from previous tests. For this test, the user requested the calculation of several additional local flow field properties. These are described in Appendix III.

3.4 UNCERTAINTY OF MEASUREMENTS

In general, instrumentation calibrations and data uncertainty estimates were made using methods recognized by the National Bureau of Standards (NBS). Measurement uncertainty is a combination of bias and precision errors defined as:

$$U = \pm(B + t_{95}S)$$

where B is the bias limit, S is the sample standard deviation and t_{95} is the 95th percentile point for the two-tailed Student's "t" distribution (95-percent confidence interval), which for sample sizes greater than 30 is taken equal to 2.

Estimates of the measured data uncertainties for this test are given in Table 2a. The data uncertainties for the measurements are determined from in-place calibrations through the data recording system and data reduction program.

Propagation of the bias and precision errors of measured data through the calculated data was made in accordance with Ref. 3 and the results are given in Table 2b.

4.0 DATA PACKAGE PRESENTATION

A sample data tabulation is presented in Appendix IV. This consists of a listing of the tunnel conditions and the theoretical wedge parameters, followed by the different types of test data. For the calibration plate the data were tabulated for each scan, ie., there was one page of pressure measurement results, followed by several pages of heat-transfer calculations, one for each time point at which the Gardon gage data were recorded. For the instrumented windshield runs the measured temperatures are tabulated at 15 second intervals and for the noninstrumented windshield runs the time of each photograph and the corresponding wedge angle are tabulated.

Since photographic data were of primary importance for the non-instrumented windshield runs, some examples are presented here. Pretest and posttest pictures of a windshield specimen are shown in Fig. 8. A gridline pattern like that in the test fixture was temporarily attached to the windshield for these pictures. Examples of the photographs obtained during a wind tunnel run are shown in Fig. 9. A wind-off tare and a run picture from camera 1 and a corresponding run picture from camera 2 are presented.

An example of the temperature histories measured in the instrumented windshield is shown in Fig. 10. The cooling air flow inside the test fixture is seen to hold the inner surface temperature constant for a few minutes. However, after about six minutes this temperature begins to rise steadily, and continues to do so through the rest of the run. It is interesting to note that this rise begins when the temperature difference between thermocouples 2S2 and 2S3 reaches about 100°F, and that this difference is maintained for as long as the data were recorded. The maximum windshield outer surface temperature applicable to the data of Fig. 10 is estimated to be about 400°F. The temperature between the outer glass and the silicone layer (2S1) of the laminated windshield is seen to rapidly approach this value.

An example of the pressure data obtained from the calibration plate is presented in Fig. 11, where the ratio of the measured surface pressure to the calculated value (simple, two-dimensional oblique shock crossing equation, see Appendix III) is shown versus spanwise distance. Data at two axial locations illustrate that near the front of the test fixture the flow behaves like two-dimensional wedge flow, while three-dimensional effects become prominent as the flow moves downstream.

In Fig. 12 the heat-transfer coefficient measured on the centerline of the calibration plate is shown as a function of axial distance. The data are compared to the theoretical values calculated from the Rockwell-supplied equation and a simple wedge theory used in the VKF. Agreement between the two theories and the data is quite good.

REFERENCES

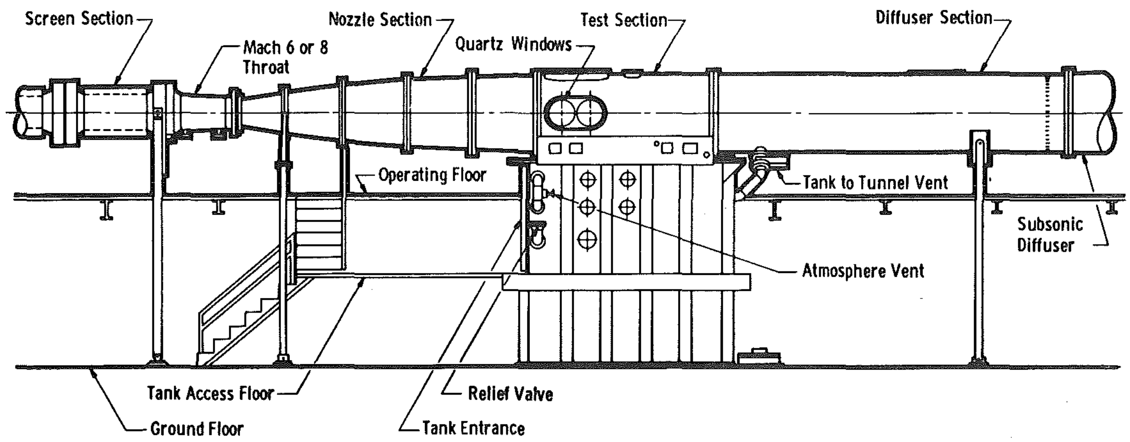
1. Matthews, R. K. and Stallings, D. W. "Materials Testing in the VKF Continuous Flow Wind Tunnels," presented at the AIAA 9th Aerodynamic Testing Conference, Arlington, TX, June 7-9, 1976.

2. Test Facilities Handbook (Eleventh Edition), "von Kármán Gas Dynamics Facility, Vol. 3." Arnold Engineering Development Center, June 1979.

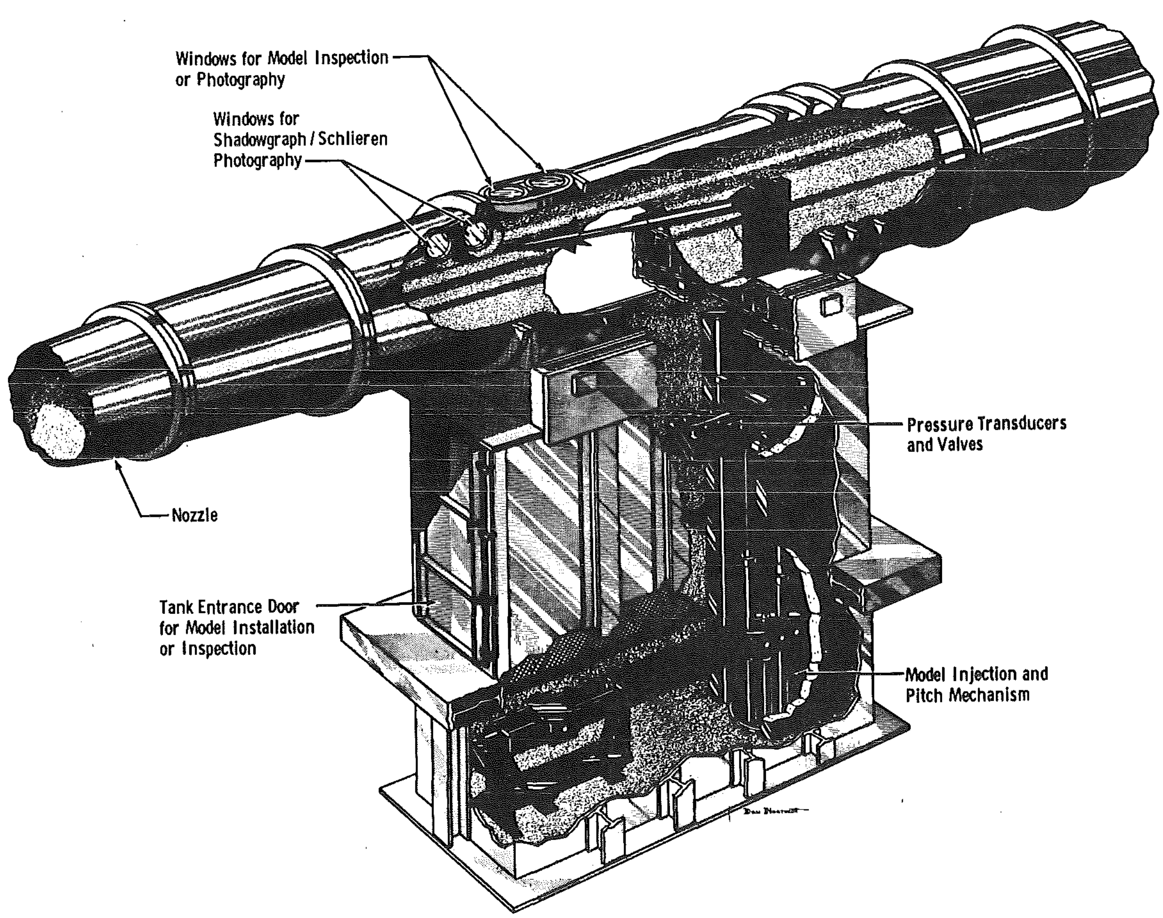
3. Thompson, J. W. and Abernethy, R. B., et al, "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD755356), February 1973.

APPENDIX I

ILLUSTRATIONS



a. Tunnel assembly



b. Tunnel test section
Figure 1. Tunnel B.

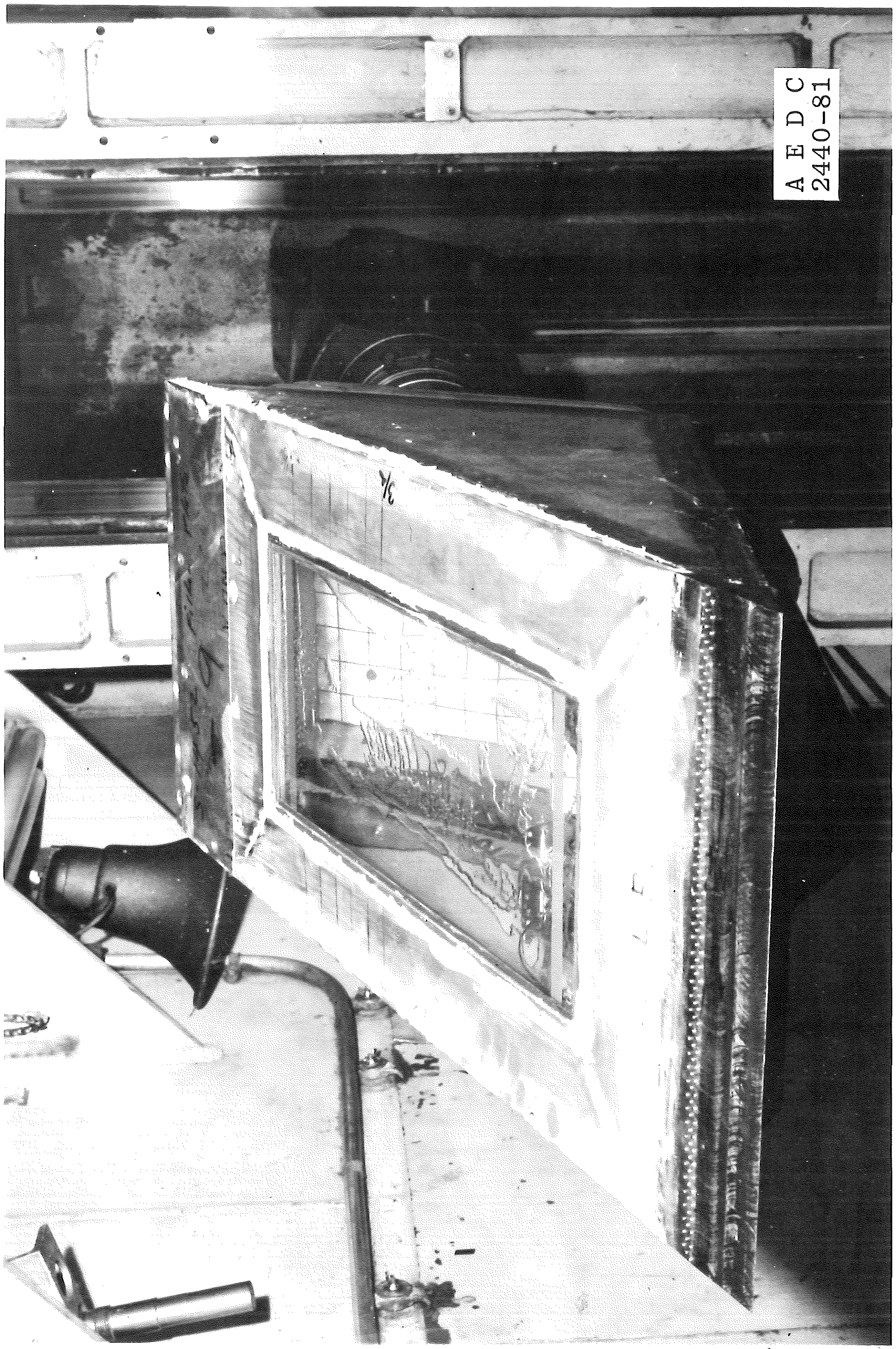


Figure 2. Photograph of Test Fixture

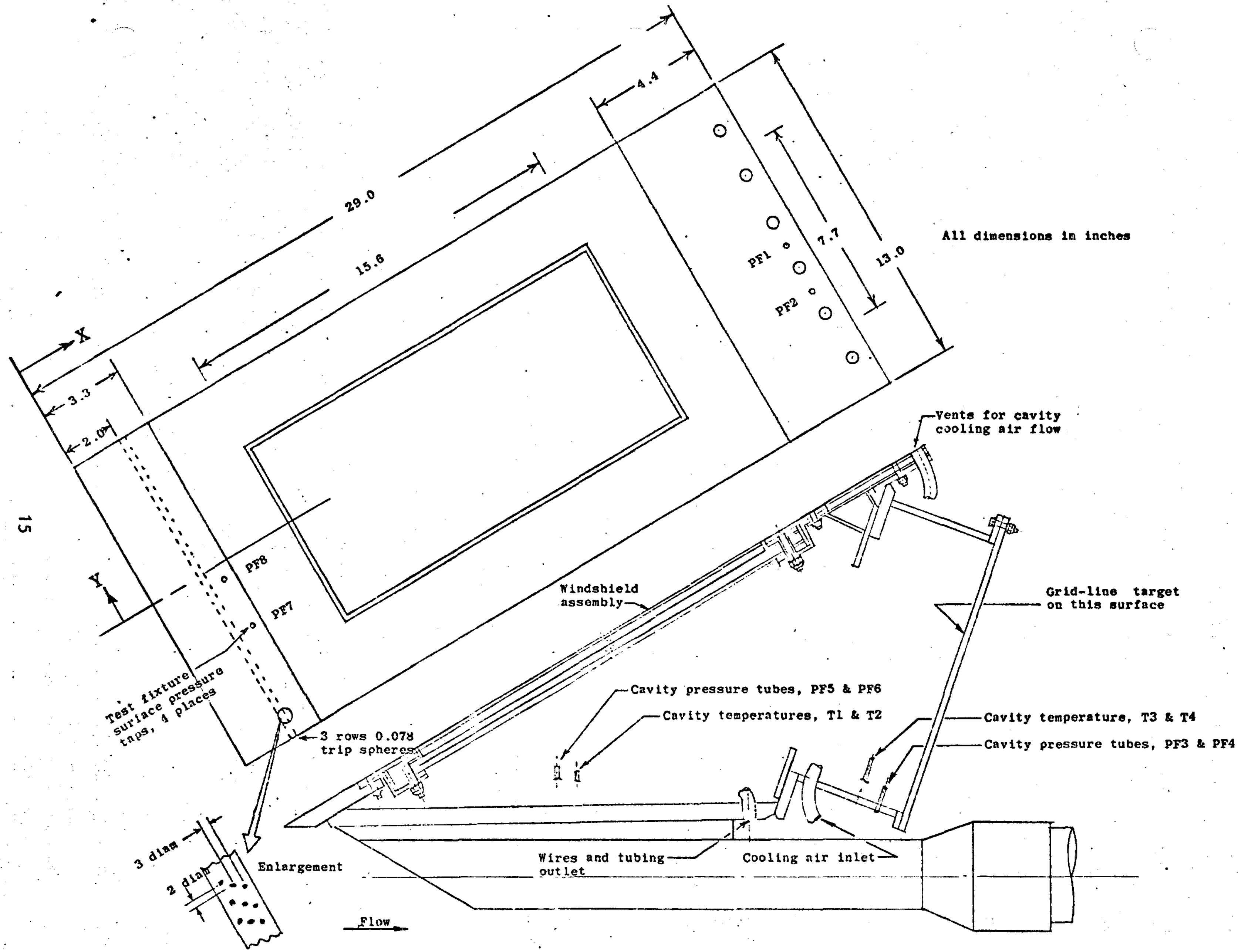
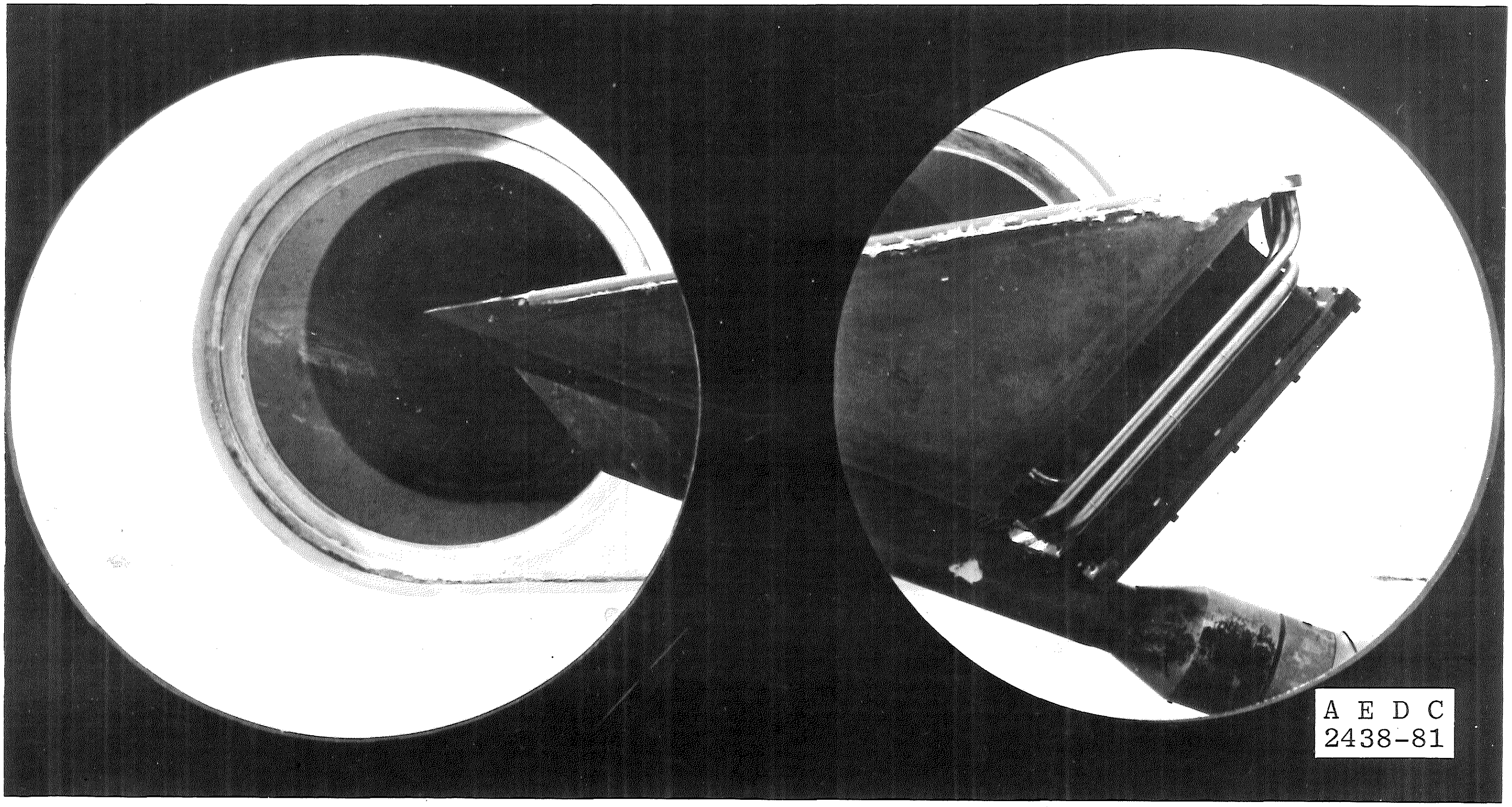
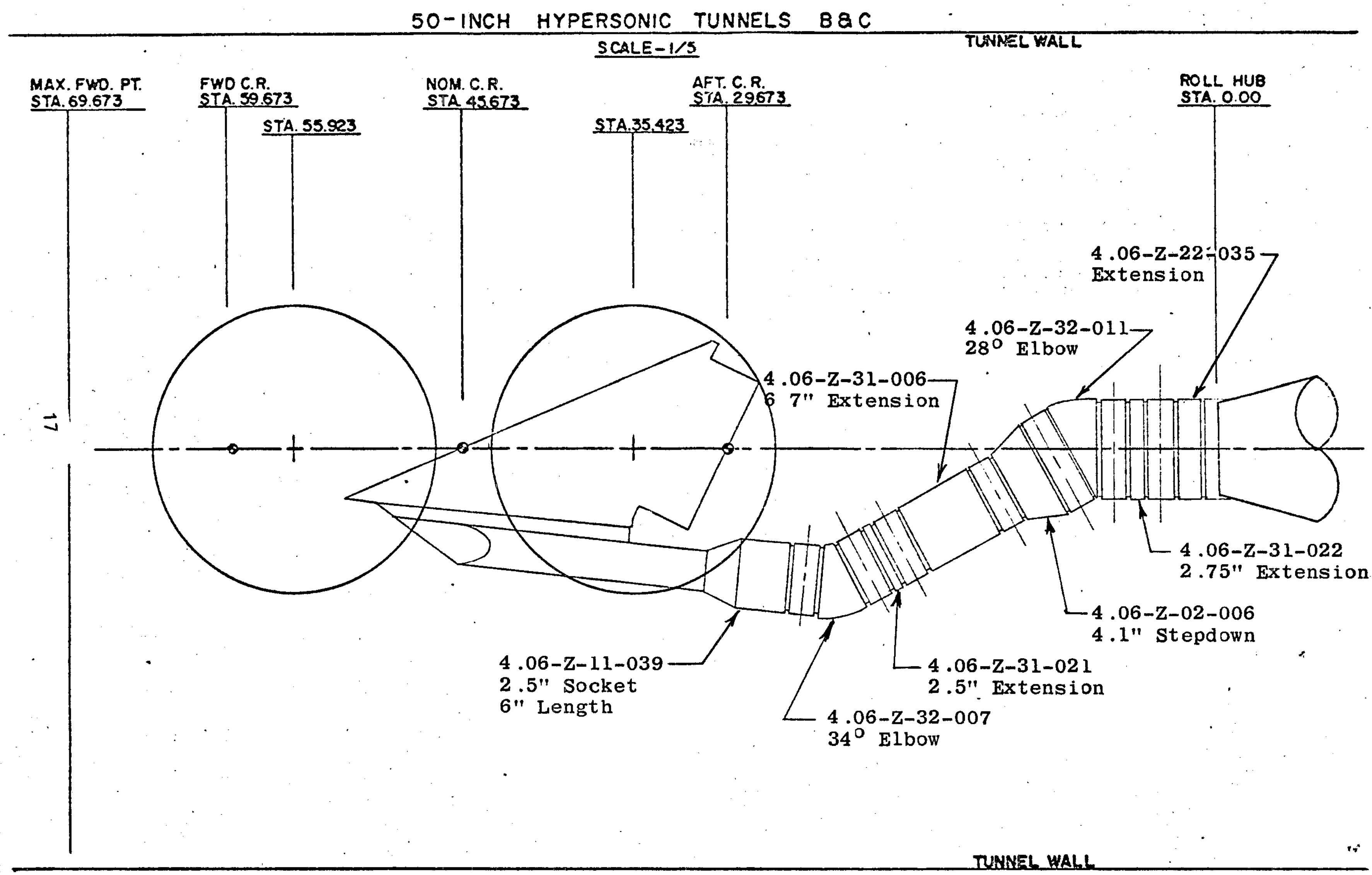


Figure 3. Details of Test Fixture Assembly



a. Installation Photograph

Figure 4. Test Fixture Installation in Tunnel B



b. Installation Sketch
Figure 4. Concluded

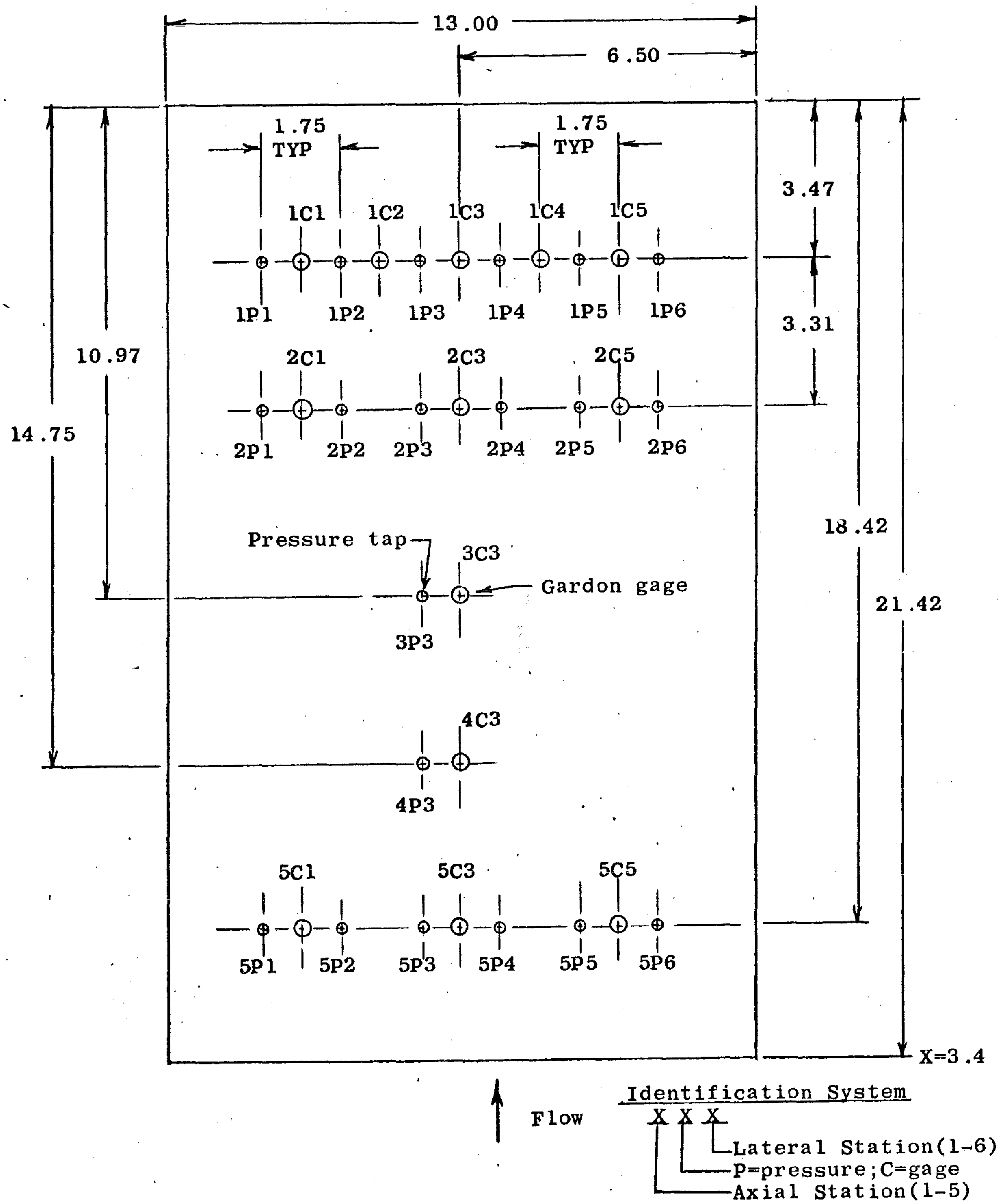


Figure 5. Sketch of Calibration Plate

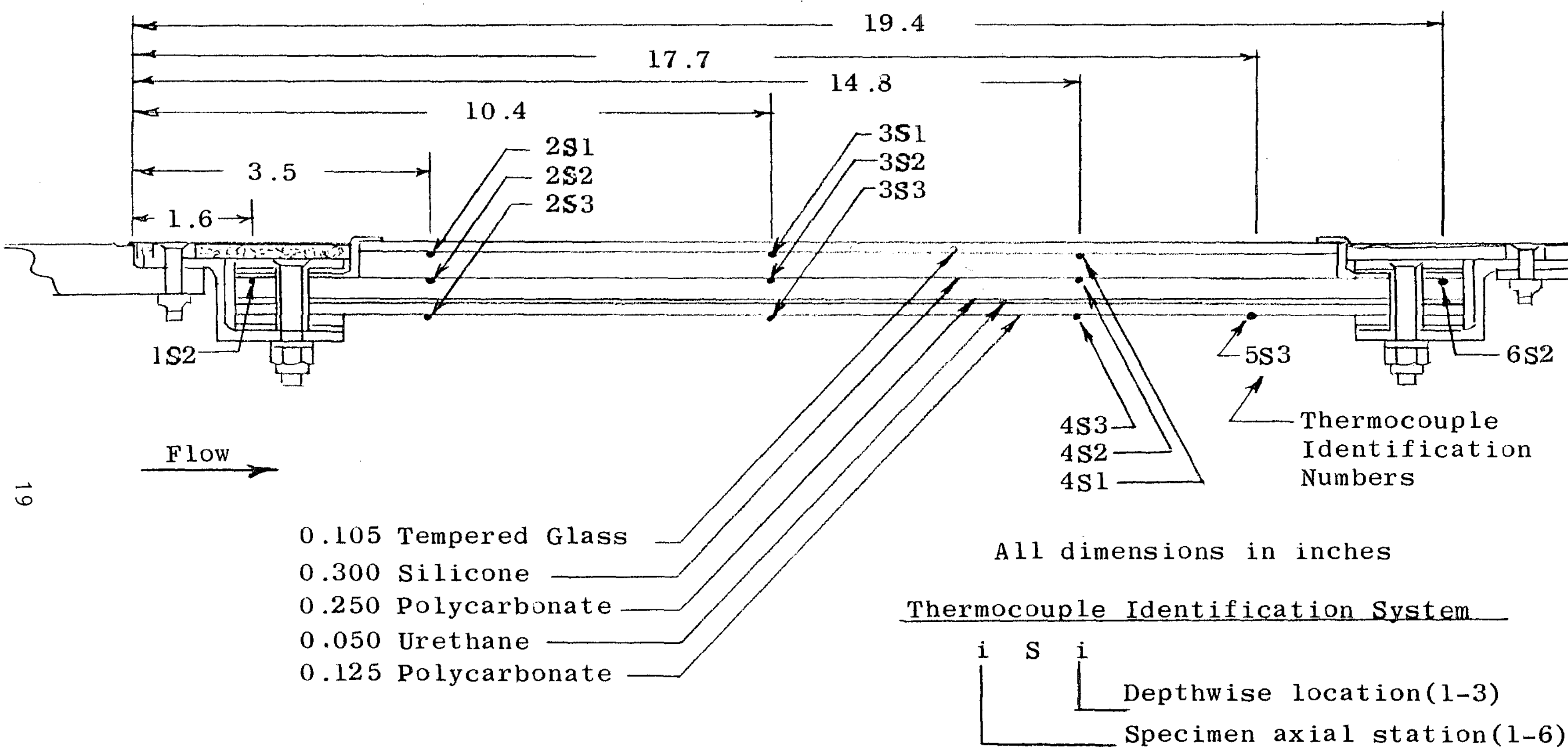


Figure 6. Sketch of Windshield Specimen

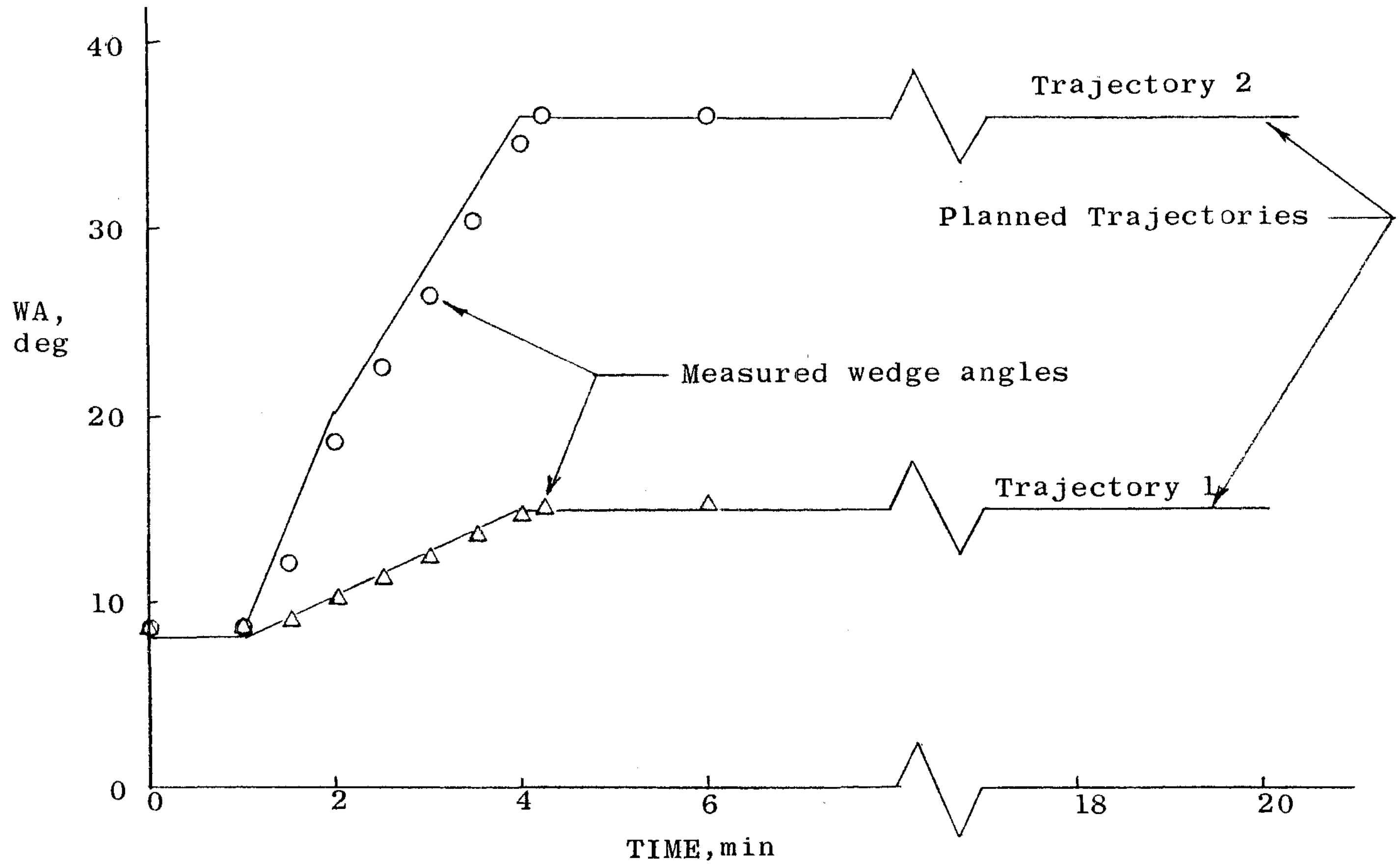


Figure 7. Wedge Angle Variation with Time

A E D C
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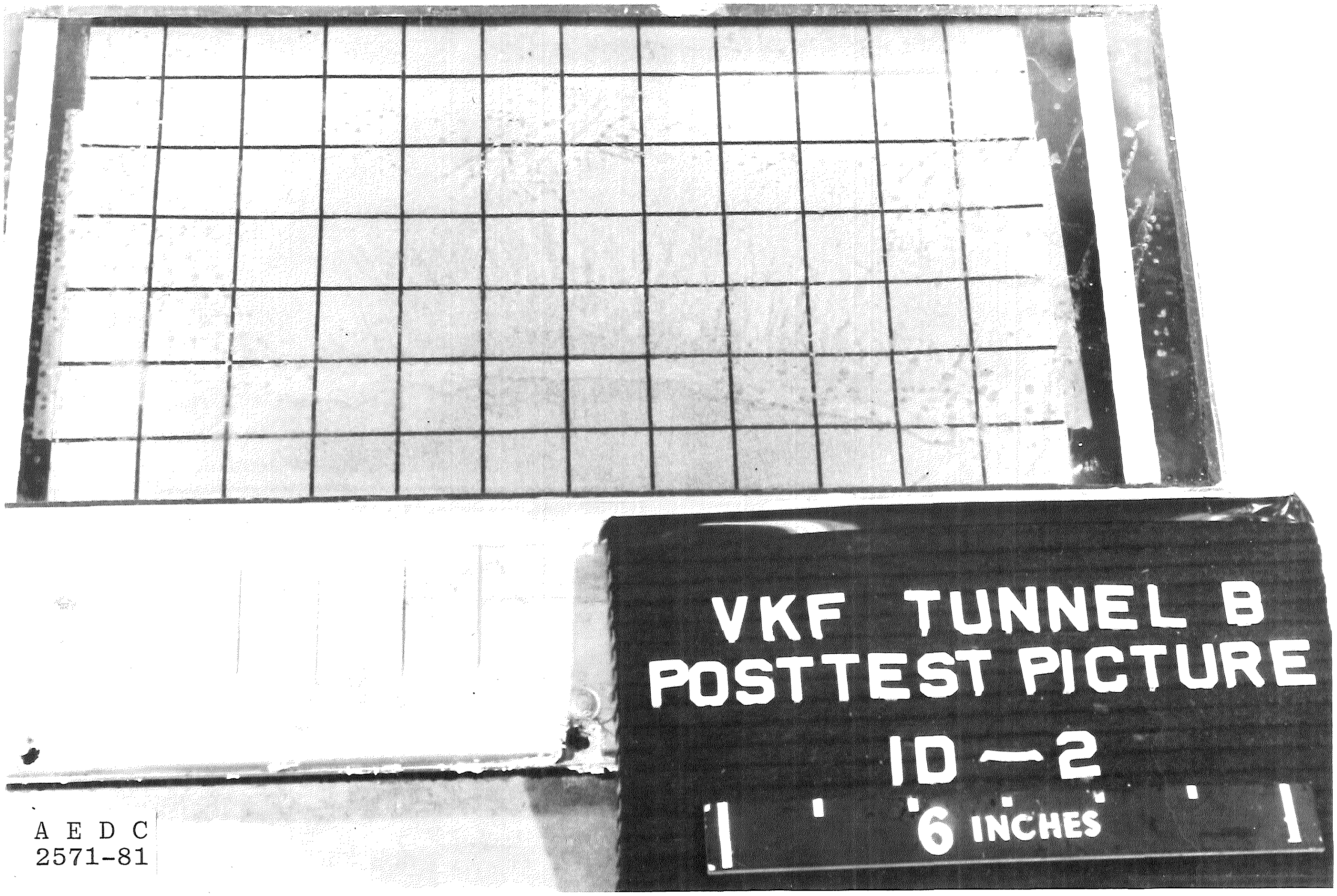
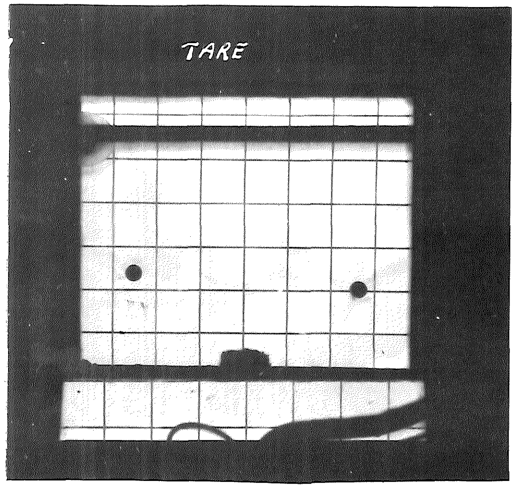
a. Pretest Picture

Figure 8. Pre- and Posttest Windshield Photographs

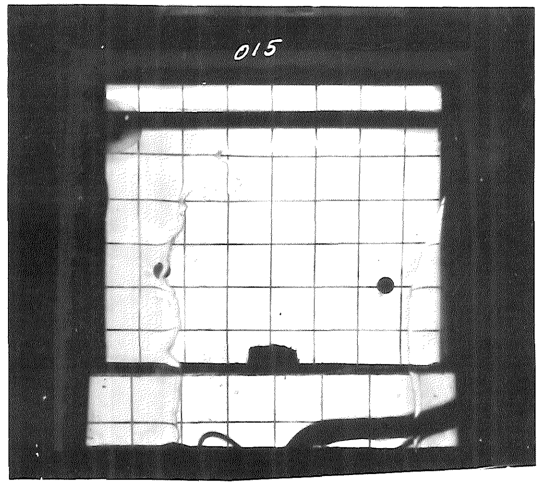


b. Posttest Picture

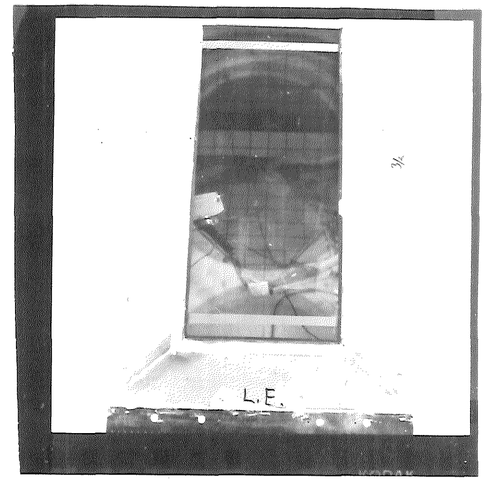
Figure 8. Concluded



Camera 1
Tare



Camera 1
Picture 2
TIME = 496 sec
WA = 8.5 deg



Camera 2
Picture 5
TIME = 496 sec
WA = 8.5 deg

Figure 9. Sample Data Photographs

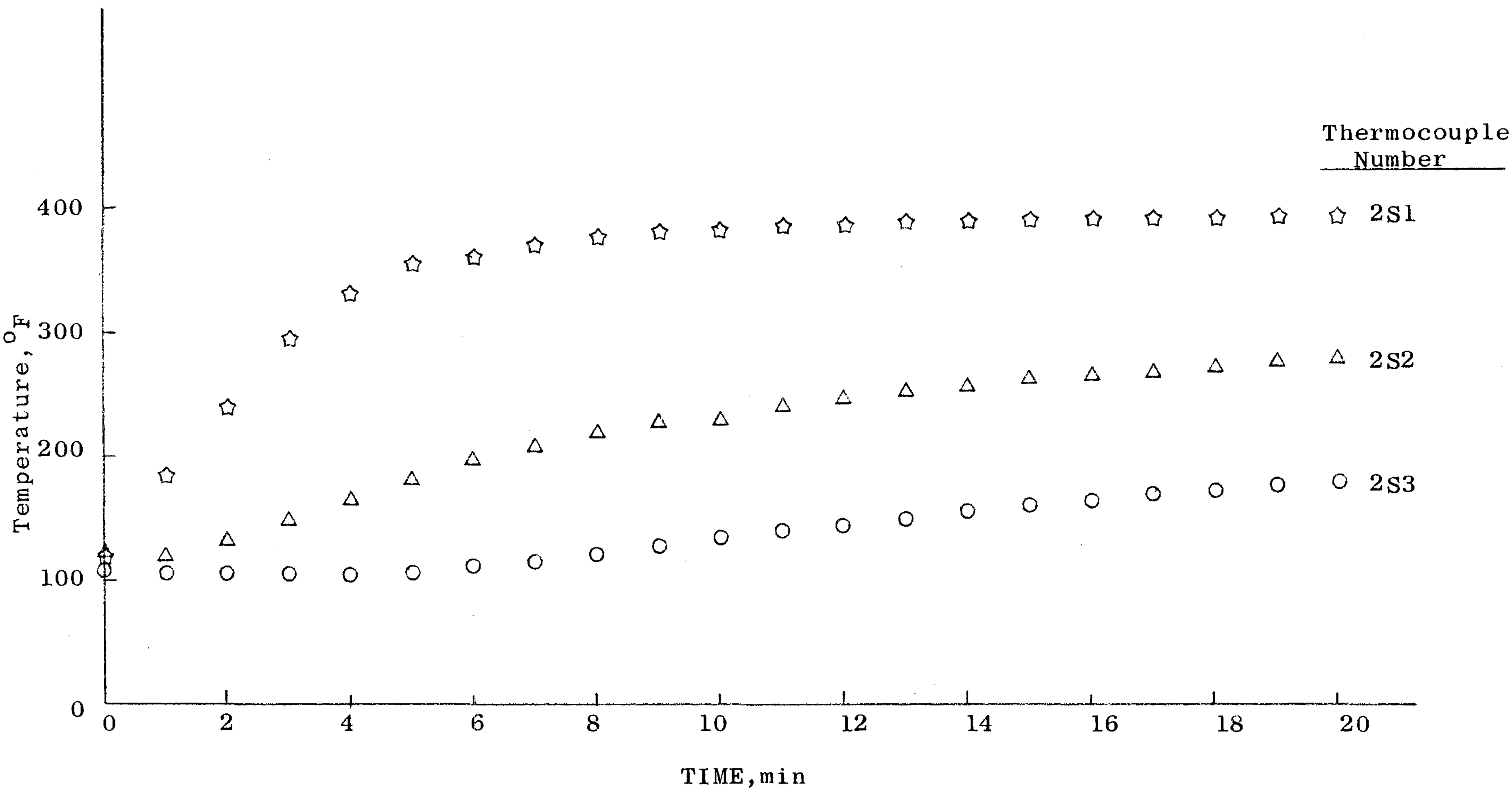


Figure 10. Example Windshield Temperature Histories

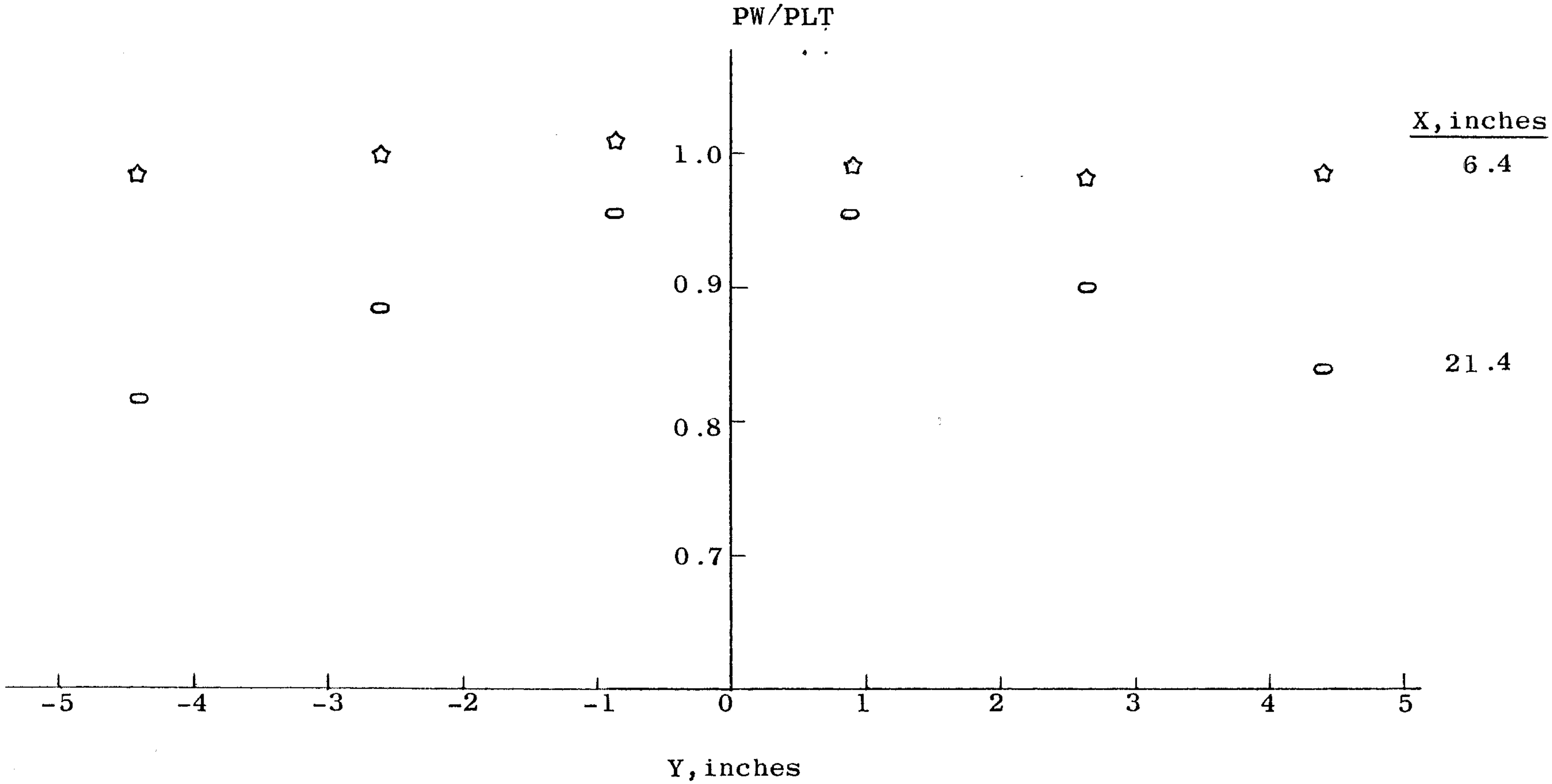


Figure 11. Sample Calibration Plate Pressure Data

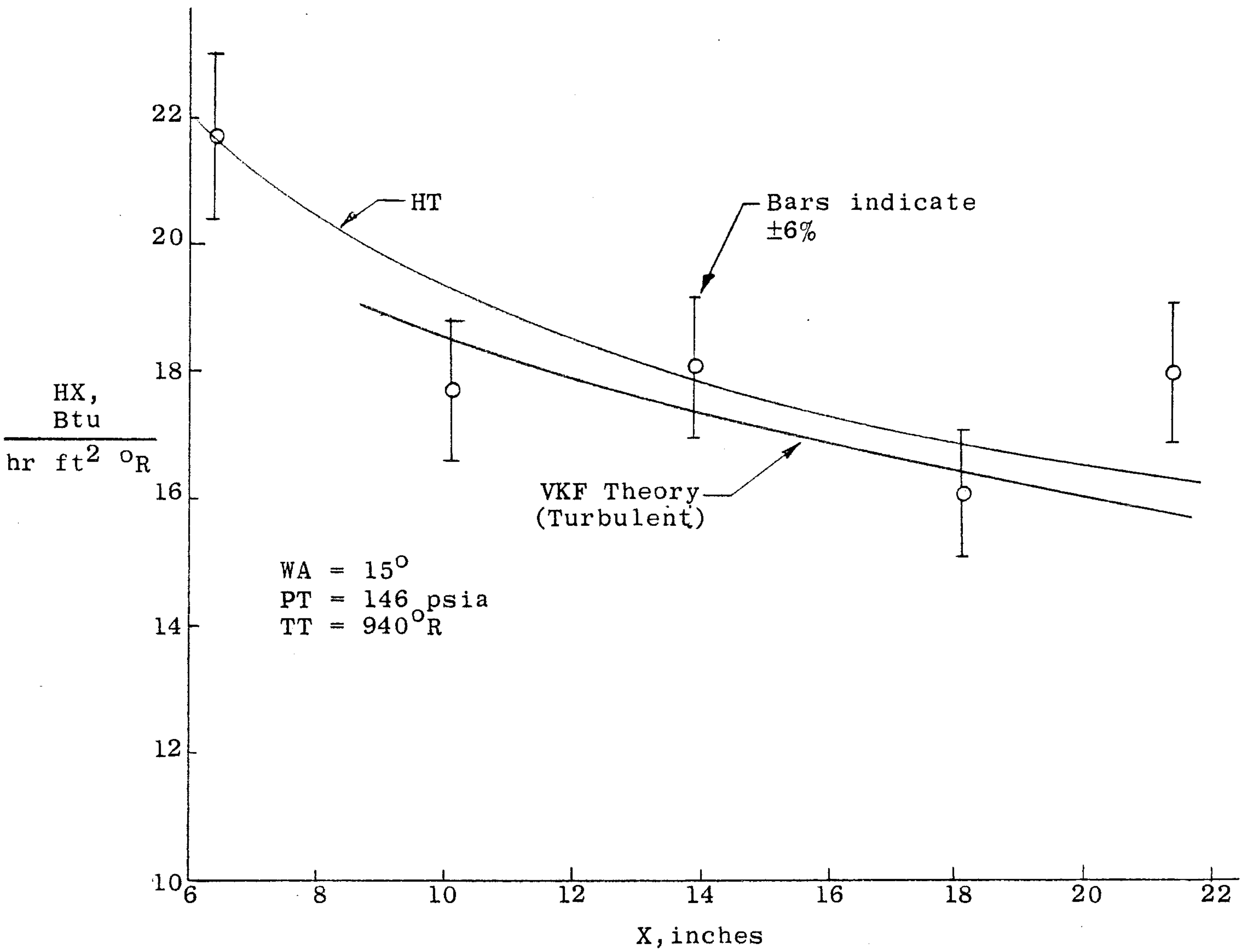


Figure 12. Sample Calibration Plate Heat-Transfer Data

APPENDIX II

TABLES

TABLE 1. Data Transmittal Summary

The following items were transmitted to the User and Sponsor.

	User	Sponsor
	Mr. V. E. Wilson Rockwell International North American Aviation Division P.O. Box 92098 Los Angeles, CA 90009	Mr. C. A. Babish AFWAL/FIER Wright-Patterson AFB, OH 45433
Items	**No. of Copies**	**No. of Copies**
Tabulated Data and Plots Vol. 1 of 1	4	1
70 mm Shadowgraph Stills, Rolls 27,28,31,32 (Runs 1-16)	1 contact print 1 duplicate negative	1 contact print 1 duplicate negative
70 mm Sequence Stills, top view of windshield, Rolls 30 & 33(Runs 11-16)	1 contact print 1 duplicate negative	1 contact print 1 duplicate negative
70 mm Sequence stills, top view of grid target, Roll 29 (Runs 11-16)	1 contact print 1 duplicate negative	1 contact print 1 duplicate negative
Pretest specimen photos, Nos. 2373-2380	2 each 8x10 prints	2 each 8x10 prints
Posttest specimen photos, Nos. 2568-2571	2 each 8x10 prints	2 each 8x10 prints
Installation photos, Nos. 2381-2384 and 2438-2440	2 each 8x10 prints	2 each 8x10 prints
Windshield installation photo before Run 11	1 each 8x10 print	1 each 8x10 print
Windshield installation photo after Run 14	1 each 8x10 print	1 each 8x10 print

TABLE 2. ESTIMATED UNCERTAINTIES

a. Basic Measurements

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT* Precision Index (S) Percent of Reading	Precision Index (S) Unit of Measurement	Precision Index (S) Degree of Freedom	Bias (B) Percent of Reading	Bias (B) Unit of Measurement	Uncertainty ±(B + t_{95}S) Percent of Reading	Uncertainty ±(B + t_{95}S) Unit of Measurement	Range	Type of Measuring Device	Type of Recording Device	Method of System Calibration
PT, psia		±0.02 ±0.02	>30 >30	±0.25	±0 26	±(0.25%	±0.30 + 0.04)	<104 <200	Bell and Howell Variable Capacitance Pressure Transducer	Digital Data Acquisition System/Analog-to-Digital Converter	In-place application of Multiple Pressure Levels Measured with a Pressure Measuring Device Calibrated in the Standards Laboratory
TT, °R		±1.0 ±1.0	>30 >30	±0.375	±2.0	±(0.375% + 2°F)	±4.0	32 to 530 530 to 2300	Chromel[R]-Alumel[R] Thermocouple	Doric Temperature Instrument/Digital Multiplexer	Thermocouple Verification of NBS Conformity by Voltage Substitution Calibration
ALPI, deg		±0.025	>30		0+		±0.05	±14	Potentiometer	Digital Data Acquisition System/Analog-to-Digital Converter	Heidenhain Rotary Encoder ROD 700 Resolution 0.0006° Overall Accuracy 0.001°
TIME		$5x10^{-4}$	>30	Runtime(sec)x5x 10^{-6}		Runtime(sec)x5x 10^{-6})+10^{-3}		ms to 365 days	Systron Donner time code generator	Digital Data Acquisition system	Instrument lab calibration against Bureau of Standards
HEAT TRANSFER, QDOT, BTU/ft²-hr	1.5	0.015	>30 >30	2 2		(0.03 + 2%) 5%		<1 1 to 10	Gardon gage	Digital data acquisition system analog-to-digital converter	Radiant heat source and secondary standard
E_{mv}	0.1		>30	0.01		(0.2% + 0.01)			DEC-10/Multiverter Preston amplifier		Milivolt standard, referenced to lab standard
TEMPERATURE, TGE, °F		1 1	>30 >30	3/8%	±2	4 (3/8% ± 2°F)		32 to 530 530 to 2300	CrAl thermocouple		

*Thompson, J. W. and Abernethy, R. B. et al. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.
+Assumed to be zero

GC-120 (2/81)

TABLE 2. Continued

b. Calculated Parameters

Parameter Designation	STEADY-STATE ESTIMATED MEASUREMENT* Precision Index (S)			Bias (B)		Uncertainty $\pm(B + t_{95}S)$		Range
	Percent of Reading	Unit of Measurement	Degree of Freedom	Percent of Reading	Unit of Measurement	Percent of Reading	Unit of Measurement	
M		0.005			0+		0.01	
P		0.00055			0.00029		0.0014	
$REx10^{-6}$		0.013			0.024		0.050	$3.0x10^{6}$
H(TT), BTU/ft^2-hr -^{o}R	2.0		30	2.0		6.0		
TW, ^{o}R	0.2		30	0.4		0.8		All
WA, deg		0.05			0+		0.10	All

*Abernethy, R. B. et al. and Thompson, J. W. "Handbook Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD 755356), February 1973.
+Assumed to be zero

TABLE 3. Gardon Gage Locations

GAGE NO.	X, in.	Y, in.
1C1	21.4	3.50
1C2		1.75
1C3		0.00
1C4		-1.75
1C5	21.4	-3.50
2C1	18.1	3.50
2C3	18.1	0.00
2C5	18.1	-3.50
3C3	13.9	0.00
4C3	10.1	0.00
5C1	6.4	3.50
5C3	6.4	0.00
5C5	6.4	-3.50

TABLE 4. Pressure Port Locations

PORT NO.	X, in.	Y, in.
1P1	21.4	4.38
1P2		2.63
1P3		0.88
1P4		-0.88
1P5		-2.63
1P6	21.4	-4.38
2P1	18.1	4.38
2P2		2.63
2P3		0.88
2P4		-0.88
2P5		-2.63
2P6	18.1	-4.38
3P3	13.9	0.88
4P3	10.1	0.88
5P1	6.4	4.38
5P2		2.63
5P3		0.88
5P4		-0.88
5P5		-2.63
5P6	6.4	-4.38

TABLE 5. Photographic Data Summary

	Camera Type	Camera View	Film Roll No.
Camera 1	Hasselblad 70 mm color still	Top View of end-line target	29
Camera 2	Hasselblad 70 mm color still	Top View of windshield	30,33
Camera 3	Sony video camera	Overhead View of test section	N/A
Camera 4	Varitron 70 mm still	Upstream side window schlieren/shadowgraph	27,31,32
Camera 5	Varitron 70 mm still	Downstream side window shadowgraph	28

TABLE 6. Test Summary

RUN	MODEL	WA,deg	PT,psia	TT, ^{o}R
1	Cal. Plate	8.5	146	955
2		15		
3		20		
4		28		
5		36		
6		8.5		1260
7		15		
8		20		
9		28		
10		36		
11	Inst. Windshield	Traj. 1		955
12		Traj. 1		
13		Traj. 2		
14		Traj. 2		1010
15	Non-inst. Windshield	Traj. 1		955
16		Traj. 2		

APPENDIX III

LOCAL FLOW FIELD PROPERTIES

The following parameters were calculated from equations provided by Rockwell International for the flow over the windshield using the calculated free-stream properties and the calibration plate heat-transfer and pressure measurements.

A. Wedge flow-field properties

1. Oblique shock wave angle (THETAT)

This is the calculated angle of the oblique shock wave formed at the leading edge of the test fixture. It is obtained by solving the cubic equation

$$\sin^6(\mathrm{THETAT}) + b \sin^4(\mathrm{THETAT}) + c \sin^2(\mathrm{THETAT}) + d = 0$$

where

$$b = \frac{M^{-2} + 2}{M^2} - 1.4 \sin^2(\mathrm{WA})$$

$$c = \frac{2M^2 + 1}{M^4} + \left(1.44 + \frac{0.4}{M^2}\right) \sin^2(\mathrm{WA})$$

$$d = -\frac{\cos^2(\mathrm{WA})}{M^4}$$

2. Local Mach number, MLT

$$\mathrm{MLT} = \left[\frac{36M^4\sin^2(\mathrm{THETAT}) - 5(M^2\sin^2(\mathrm{THETAT})-1)(7M^2\sin^2(\mathrm{THETAT})+5)}{(7M^2\sin^2(\mathrm{THETAT})-1)(M^2\sin^2(\mathrm{THETAT})+5)}\right]^{1/2}$$

3. Local static pressure, PLT

$$\mathrm{PLT} = P\left[\frac{7M^2\sin^2(\mathrm{THETAT})-1}{6}\right]$$

4. Local static temperature, TLT

$$\mathrm{TLT} = \mathrm{TT}\left[1 + \frac{(\mathrm{MLT})^2}{5}\right]^{-1}$$

5. Local velocity, VELT

$$VELT = 49.04\ (MLT)\sqrt{TLT}$$

B. Theoretical heat-transfer parameters

These parameters were calculated for each Gardon gage on the calibration plate runs

1. Pressure ratio, CHI

$$CHI = \frac{PW)_{avg}}{P}$$

where

$PW)_{avg}$ is the average of the two static pressure measurements adjacent to a given Gardon gage

2. Experimental local Mach number, MLX

$$MLX = \left[\frac{M^2(6(CHI) + 1) - 5((CHI)^2 \ -1)}{(CHI)(CHI + 6)}\right]^{1/2}$$

3. Experimental local static temperature, TLX

$$TLX = T(CHI)\left(\frac{CHI + 6}{6(CHI) + 1}\right)$$

4. Experimental adiabatic wall temperature, AWX

$$AWX = TLX\left[1 + 0.176(MLX)^2\right]$$

5. Gage-to-tunnel-wall radiant heat flux, QSW

$$QSW = 0.1543 \times 10^{-8}\left[(TW)^4 - (TST)^4\right]$$

6 Experimental heat-transfer coefficient, HX

$$HX = \frac{QDOT + QSW}{AWX - TW}$$

7. Theoretical reference temperature, T*T

$$T{*}T = 0.5\ (TLT + TW) + 0.161\left(\frac{VELT}{100}\right)^2$$

8. Theoretical recovery factor, REC

$$\text{REC} = \left(0.64 + \frac{38.13}{\text{T*T+52}}\right)^{1/3}$$

9. Theoretical adiabatic wall temperature, AWT

$$\text{AWT} = \left(\text{TLT}\right) \times \left[1 + 0.2(\text{REC})(\text{MLT})^2\right]$$

10. Theoretical reference temperature functions, PHI

$$\text{PHI} = 0.655 + \frac{1122}{\text{T*T} + 91.3}$$

11. Theoretical heat-transfer coefficient, HT

$$\text{HT} = \frac{0.0192(\text{PHI})\left[(\text{PLT})(\text{VELT})\right]^{0.8}}{\text{L}^{0.2}}$$

APPENDIX IV

SAMPLE TABULATED DATA

DATE COMPUTED .0-APR-81
DATE RECORDED 9-APR-81
TIME RECORDED 1:17:34
PROJECT NO V41B-01

VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENN
AFWAL/RI HIGH TEMP WINDSHIELD

PAGE 2

RUN	MODEL	M	PT,PSIA	TT,DEG R	ALPI,DEG	WA,DEG	RE,FT-1	TIME,SEC	LOOP
2	CALIBRATION PLATE	5.94	146.3	941.7	8.06	14.94	0.237E+07	31.48	4

T DEG R	P PSIA	MDOT LBM/MIN	THETAT DEG	MLT	VELT FT/SEC	PLT PSIA	TLT DEGR	TST DEGR	TIMEINJ SEC
116.9	0.099	-0.00	22.69	3.97	2932.	0.59	226.623	540.14	7.75

CAVITY PRESSURE, PSIA				CAVITY TEMP, DEGF				WEDGE PRESSURE PSIA				DELTA PRESSURES, PSID	
PF3	PF4	PF5	PF6	T1	T2	T3	T4	PF1	PF2	PF7	PF8	PF5-7	PF6-2
0.4	0.4	0.4	0.4	537.0	537.8	583.5	588.7	0.49	0.46	0.58	0.59	-0.151	-0.039

CALIBRATION PLATE PRESSURE DATA

PORT NO	X IN.	Y IN.	PW PSIA	PW/P	PW/PLT
1P1	21.4	4.375	0.493	4.989	0.838
1P2	21.4	2.625	0.528	5.347	0.898
1P3	21.4	0.875	0.561	5.683	0.954
1P4	21.4	-0.875	0.561	5.681	0.954
1P5	21.4	-2.625	0.520	5.264	0.884
1P6	21.4	-4.375	0.480	4.858	0.816
2P1	18.1	4.375	0.490	4.961	0.833
2P2	18.1	2.625	0.537	5.438	0.913
2P3	18.1	0.875	0.563	5.701	0.957
2P4	18.1	-0.875	0.559	5.663	0.951
2P5	18.1	-2.625	0.530	5.371	0.902
2P6	18.1	-4.375	0.479	4.852	0.815
3P3	13.9	0.875	0.573	5.808	0.975
4P3	10.1	0.875	0.581	5.887	0.989
5P1	6.4	4.375	0.579	5.860	0.984
5P2	6.4	2.625	0.578	5.850	0.982
5P3	6.4	0.875	0.583	5.909	0.992
5P4	6.4	-0.875	0.596	6.037	1.014
5P5	6.4	-2.625	0.588	5.958	1.001
5P6	6.4	-4.375	0.578	5.858	0.984

Sample 1. Calibration Plate Pressure Data

VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENN
AFWAL/RI HIGH TEMP WINDSHIELD

DATE COMPUTED -APR-81
DATE RECORDED 9-APR-81
TIME RECORDED 1:17:34
PROJECT NO V41B-01

PAGE 3

RUN	MODEL	M	PT,PSIA	TT,DEG R	ALPI,DEG	WA,DEG	RE,FT-1	TIME,SEC	LOOP
2	CALIBRATION PLATE	5.94	146.1	940.7	8.06	14.94	0.237E+07	9.95	3

T DEG R	P PSIA	MDOT LBM/MIN	THETAT DEG	MLT	VELT FT/SEC	PLT PSIA	TLT DEGR	TST DEGR	TIMEINJ SEC
116.8	0.099	-0.00	22.69	3.97	2931.	0.59	226.385	540.23	7.75

CAVITY PRESSURE, PSIA				CAVITY TEMP, DEGF				WEDGE PRESSURE PSIA				DELTA PRESSURES, PSID	
PF3	PF4	PF5	PF6	T1	T2	T3	T4	PF1	PF2	PF7	PF8	PF5-7	PF6-2
0.0	0.0	0.0	0.0	536.9	537.6	581.7	588.7	0.00	0.00	0.00	0.00	-0.000	-0.000

CALIBRATION PLATE HEAT TRANSFER DATA

GAGE NO	X IN	Y IN	TGE DEG F	TW DEG R	QDOT BTU/HRFT2	CHI	MLX	TLX DEG R	AWX DEG R	H(TT) BTU/HR FT2 DEG R
1C1	21.4	3.50	572.8	575.9	4507.3	5.161	4.16	210.9	854.9	12.357
1C2	21.4	1.75	572.9	576.2	4753.0	5.507	4.08	217.9	855.7	13.039
1C3	21.4	0.00	573.3	576.8	4988.3	5.675	4.04	221.3	856.1	13.708
1C4	21.4	-1.75	572.3	575.6	4693.7	5.465	4.09	217.1	855.6	12.856
1C5	21.4	-3.50	572.2	575.1	4361.1	5.055	4.19	208.8	854.6	11.931
2C1	18.1	3.50	571.2	573.8	3689.0	5.193	4.16	211.6	854.9	10.054
2C3	18.1	0.00	572.0	575.1	4486.1	5.675	4.04	221.3	856.1	12.271
2C5	18.1	-3.50	572.6	575.8	4560.4	5.105	4.18	209.8	854.7	12.497
3C3	13.9	0.00	570.1	573.6	5072.5	5.801	4.01	223.8	856.4	13.819
4C3	10.1	0.00	569.7	573.1	4988.1	5.880	3.99	225.4	856.6	13.571
5C1	6.4	3.50	571.9	575.7	5484.7	5.847	4.00	224.7	856.5	15.029
5C3	6.4	0.00	560.7	565.1	6290.6	5.965	3.97	227.1	856.8	16.750
5C5	6.4	-3.50	574.4	578.4	5954.4	5.900	3.98	225.8	856.6	16.438

QSW BTU/HRFT2	HX BTU/HRFT2 DEGR	T*T DEG R	REC	AWT DEG R	PHI	L FT	HT BTU/HRFT2 DEGR	HX/HT
38.32	16.296	539.4	0.890	230.2	2.434	1.680	16.330	0.998
38.60	17.141	539.6	0.890	230.2	2.434	1.680	16.328	1.050
39.32	17.998	539.9	0.890	230.2	2.433	1.680	16.322	1.103
37.90	16.897	539.3	0.890	230.2	2.434	1.680	16.333	1.034
37.41	15.739	539.0	0.890	230.2	2.435	1.680	16.337	0.963
35.79	13.247	538.4	0.890	230.2	2.437	1.400	16.958	0.781
37.35	16.097	539.0	0.890	230.2	2.435	1.400	16.944	0.950
38.13	16.484	539.4	0.890	230.2	2.434	1.400	16.938	0.973
35.61	18.063	538.3	0.890	230.2	2.437	1.050	17.963	1.006
35.03	17.719	538.0	0.890	230.2	2.438	0.740	19.271	0.919
38.09	19.669	539.3	0.890	230.2	2.434	0.430	21.449	0.917
25.93	21.655	534.0	0.890	230.2	2.449	0.430	21.582	1.003
41.32	21.552	540.7	0.890	230.2	2.430	0.430	21.415	1.006

Sample 2. Calibration Plate Heat-Transfer Data

VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENN
AFWAL/RI HIGH TEMP WINDSHIELD

DATE COMPUTED -MAY-81
DATE RECORDED -APR-81
TIME RECORDED 5: 7:19
PROJECT NO V41B-01

INSTRUMENTED TRANSPARENCY DATA

RUN	MODEL	M	PT, PSIA	TT, DEG R	ALPI, DEG	WA, DEG	RE, FT-1	TIME, SEC	LOOP
13	INSTRUMENTED TRANSPARENCY	5.94	146.9	960.7	14.48	8.52	0.231E+07	0.00	1

T DEG R	P PSIA	MDOT LBM/MIN	THETAT DEG	MLT	VELT FT/SEC	PLT PSIA	TLT DEGR	TST DEGR	TIMEINJ SEC
119.3	-0.001	0.00	16.29	4.80	3081.	0.30	171.081	543.36	1.16

CAVITY PRESSURE, PSIA				CAVITY TEMP, DEGF				WEDGE PRESSURE PSIA				DELTA PRESSURES, PSID	
PF3	PF4	PF5	PF6	T1	T2	T3	T4	PF1	PF2	PF7	PF8	PF5-7	PF6-2
0.0	0.0	0.0	0.0	83.8	83.5	85.8	85.3	0.00	0.00	0.00	0.00	0.000	0.000

TIME		WINDSHIELD TEMPERATURE, DEG F											
MIN	WA	6S2	5S3	4S1	4S2	4S3	3S1	3S2	3S3	2S1	2S2	2S3	1S2
0.00	8.52	90.4	103.2	112.2	117.6	104.5	108.9	114.1	98.9	112.8	117.5	106.1	111.6
0.25	8.44	89.9	102.3	127.3	117.2	103.6	119.9	113.7	98.0	125.9	117.3	105.5	111.0
0.50	8.44	89.4	102.3	153.3	116.8	103.4	140.3	113.5	98.0	148.9	117.5	105.5	110.9
0.75	8.44	89.2	101.5	174.9	116.9	103.2	157.8	113.6	97.6	168.1	118.6	105.3	110.4
1.01	8.44	89.5	101.4	192.8	118.3	102.4	173.1	114.6	97.4	184.1	120.3	105.3	110.0
1.26	9.18	90.3	101.2	207.7	120.0	102.6	185.8	116.2	97.3	197.6	122.8	105.0	110.1
1.51	11.98	91.2	100.5	220.5	122.3	102.0	198.4	118.1	96.9	210.3	125.7	104.5	109.7
1.76	14.92	92.6	100.5	234.4	125.2	101.9	211.9	120.7	97.0	224.6	128.4	104.1	110.0
2.01	17.91	94.1	100.1	248.4	128.5	101.6	226.2	123.3	96.9	239.6	131.9	103.8	110.3
2.26	20.53	96.0	100.1	262.2	132.0	101.6	241.2	126.4	96.9	255.2	135.5	103.3	110.7
2.51	22.44	98.2	100.1	274.8	135.8	101.6	255.9	129.7	97.0	269.6	139.2	103.3	111.2
2.77	24.35	100.5	100.0	286.9	139.4	101.6	269.5	133.3	97.2	282.5	143.2	103.5	111.8
3.02	26.28	102.7	100.0	297.9	143.1	101.5	282.3	136.7	97.4	294.4	147.3	103.2	112.2
3.27	28.32	105.4	100.1	307.8	147.1	101.8	293.9	140.9	97.7	304.8	151.5	103.6	113.2
3.50	30.03	108.0	100.3	316.7	151.2	102.0	303.4	144.7	97.6	313.7	155.3	103.5	114.1
3.75	31.95	110.7	100.2	324.8	155.0	102.2	311.9	148.8	97.8	322.4	159.6	103.9	114.9
4.00	34.00	113.6	100.7	332.5	159.4	102.5	319.9	153.0	98.2	330.4	163.8	104.5	115.9
4.25	36.02	116.6	100.9	339.6	163.3	103.1	327.3	157.1	98.5	337.7	168.2	104.7	117.0
4.55	36.05	120.2	101.5	346.7	168.0	103.9	335.5	162.1	99.2	345.2	173.1	105.6	118.6
4.80	36.05	123.5	102.0	351.5	171.9	104.5	341.0	166.4	99.7	350.3	177.1	106.5	119.9
5.06	36.05	126.6	102.5	354.9	176.0	105.1	345.4	170.0	100.2	354.3	181.1	107.0	121.2

Sample 3. Instrumented Windshield Data

VON KARMAN GAS DYNAMICS FACILITY
ARNOLD AIR FORCE STATION, TENN
AFWAL/RI HIGH TEMP WINDSHIELD

DATE COMPUTED 11 [illegible]Y-81
DATE RECORDED 10-APR-81
TIME RECORDED 7: 6:18
PROJECT NO V41B-01

PAGE 1

RUN	MODEL	M	PT,PSIA	TT,DEG R	ALPI,DEG	WA,DEG	RE,FT-1	TIME,SEC	LOOP
15	OPTICAL TRANSPARENCY	5.94	146.9	960.7	14.41	8.59	0.231E+07	0.00	1

T DEG R	P PSIA	MDOT LBM/MIN	THETAT DEG	MLT	VELT FT/SEC	PLT PSIA	TLT DEGR	TST DEGR	TIMEINJ SEC
119.3	0.099	-0.00	16.35	4.80	3080.	0.31	171.561	543.43	5.35

CAVITY PRESSURE, PSIA				CAVITY TEMP, DEGF				WEDGE PRESSURE PSIA				DELTA PRESSURES, PSID	
PF3	PF4	PF5	PF6	T1	T2	T3	T4	PF1	PF2	PF7	PF8	PF5-7	PF6-2
0.0	0.0	0.0	0.0	563.1	562.8	569.5	572.1	0.00	0.00	0.00	0.00	0.000	0.000

PHOTOGRAPHIC DATA

TOP 1 PICTURE NUMBER	TIME	WA
1	10.28	8.45
2	495.79	8.47
3	733.34	8.47
4	970.84	8.47
5	1271.92	8.47

TOP 2 PICTURE NUMBER	TIME	WA
1	10.28	8.45
2	15.91	8.52
3	169.76	11.88
4	259.81	14.99
5	495.79	8.47
6	733.34	8.47
7	767.68	14.99
8	970.84	8.47
9	1271.92	8.47

Sample 4. Non-instrumented Windshield Data